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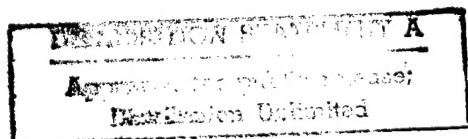
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A High-Power Electrically Driven Impulsive Acoustic Source for Target Effects Experiments and Area-Denial Applications*

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I. Introduction and Background

A variety of acoustic sources are being developed and tested for possible application as special weapons for use in scenarios such as crowd control and area denial that call for less-than-lethal force application. These sources include devices that generate acoustic energy by repetitive combustion or detonation of a fuel-oxidizer mixture. These devices are attractive for development as fieldable weapons because they offer the advantages of simplicity of design and very high-intensity acoustic output from relatively small packages powered by common chemical fuels. The acoustic signals produced by these devices are typically repetitive impulsive waveforms similar to those generated by explosives and are characterized by an initial short-risetime, high positive sound pressure level (SPL) that falls roughly exponentially to a lower-level negative-pressure undershoot. The duration of the positive-pressure phase or pulse is typically on the order of a millisecond. In an effort to deliver significant average acoustic power and possibly excite low-frequency resonances or other nonaural response modes in a target, some of these impulsive combustion sources (ICS's) generate a train of impulses at rates on the order of 10 Hz.

Unfortunately, little is known about the effects of such repetitive ICS waveforms on potential targets at intensities of interest for less-than-lethal weapons applications. Data do exist for the physical effects of impulsive waveforms at high levels (e.g., blast overpressure effects) and for the auditory effects of such waveforms at much lower levels. However, the orders of magnitude of SPL separating these effects are largely unexplored and laboratory studies are needed. However, combustion- or detonation-driven devices are not "user-friendly" as laboratory sources, especially for indoor experimentation. In addition to the safety considerations associated with the use of fire or explosive materials, these devices can produce noxious exhaust products. They are also not well-suited to long-term systematic experimentation where ease of use and accurately repeatable performance are important considerations. As a consequence, we identified a near-term need for a user- and laboratory-friendly acoustic source that can support target effects studies and source design optimization by providing a reasonable simulation of both the waveform and SPL expected from an ICS at range on a target.

The Sequential Arc Discharge Acoustic Generator (SADAG) produces high-intensity impulsive sound waves by purely electrical means and is both user- and environment-friendly. Sound is generated in the SADAG by the sudden expansion of ionized gases produced when electrical discharges occur in air. The electrical discharges or arcs take place between electrodes in an insulating tube closed at one end and open at the other to direct the shock front (pressure wave) from the discharges to the target. The high-energy arcs are driven by electrical charge stored on high-voltage (HV) capacitors. A primary feature of the SADAG is the use of multiple arcs or discharges occurring in sequence, rather than a single arc, to generate the output acoustic waveform. This

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has two major advantages. First, the pulse width of the acoustic output may be extended and adjusted by timing the overlay of pulses from individual arcs. Second, multiple arcs are more efficient than a single arc at converting electrical energy to acoustic energy.

In operation, the prototype electrical-discharge source reliably generates impulsive waveforms at peak SPLs comparable to combustion sources at useful laboratory ranges. The source can be operated in a single-shot, repetitive, or burst mode at rates to above 20 pulses/s. The source has been employed in a critical series of target effects experiments. Further, the source technology shows promise for near-term use in facility area-denial applications.

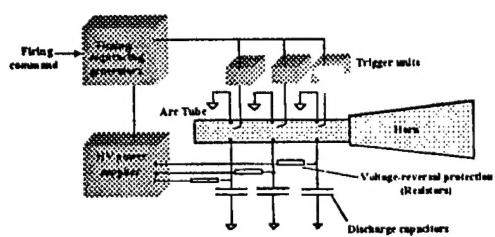


Figure 1. Block diagram of SADAG.

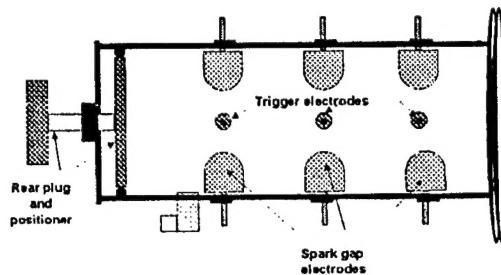


Figure 2. Detail of SADAG arc tube.

II. Description and Physics of the Device

Figure 1 is a block diagram of one embodiment of the SADAG, and figure 2 is a detail of the arc tube. In this version, three spark gaps are spaced at roughly 2-in. intervals along the length of the 2-in.-diameter, 10-in. insulating arc tube that is closed at one end with an adjustable end plate and open at the other end into a conical horn. The arc tube also includes a gas line fitting to allow the flow of nitrogen gas through the tube during operation to minimize ozone production (if required by the laboratory facility) and to provide some cooling of the tube and spark gaps for long-duration runs. The spark gaps are pairs of hemispherical electrodes mounted on opposite sides of the tube. Each gap is connected across two parallelled 2- μ F, 30-kV capacitors. These capacitors are charged through series resistors by one or more high-voltage power supplies. Small trigger electrodes are also mounted on the arc tube wall at each gap, equidistant from the primary electrodes. They are connected to high-voltage trigger units that consist of automotive ignition coils and MOSFET switches. A timing/trigger generator controls source operation. This unit may be preset to cause the source to generate a single acoustic pulse upon receiving a firing command (by a manual pushbutton or electrical pulse; e.g., from a random-sequence generator) or up to 999 pulses per firing command at rates up to 20 pulses/s (burst operation). To produce each acoustic pulse, the timing circuit generates sequenced signals that activate the HV power supplies to charge the energy storage capacitors, arm the trigger units (energize the ignition coils), and then fire the trigger units in quick succession at preset intervals. When a trigger unit fires, it applies a HV transient (> 40 kV peak) to the trigger electrode located near the main spark gap. The large transient electric field in the vicinity of the sharp electrode that results causes local air breakdown (ionization) that leads quickly to air-ion avalanching and a high-current arc discharge between the main electrodes. (Discharge through the trigger electrode is limited to low currents by the inductance and resistance (resistor wire) of the ignition coil secondary circuit.)

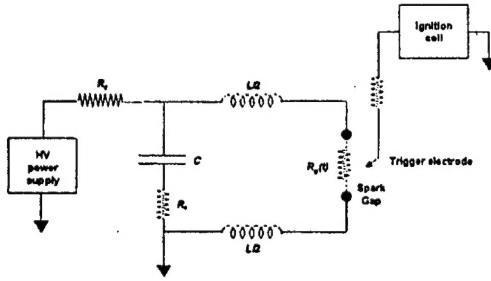


Figure 3. Equivalent circuit of one spark gap for SADAG.

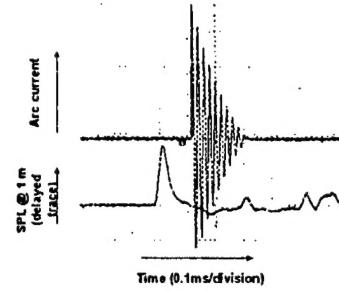


Figure 4. Upper trace: Measured current waveform for SADAG discharge. Lower trace: Acoustic pulse recorded at 1 m from source.

The equivalent circuit of a single spark gap and HV capacitor is shown in figure 3. R_c is the series charging resistance ($2\text{ k}\Omega$), C is the HV storage capacitance, R_s is the total effective dc series resistance of C and the leads from C to the spark gap, L is the series inductance of C and the leads (assumed equal in each lead), and $R_g(t)$ is the time-dependent series resistance of the arc channel ($R_g(0) = \infty$). R_c effectively isolates the HV supply from voltage transients from the capacitor discharge circuit when the spark gap fires; therefore during the arc discharge the equivalent circuit is the simple series $R-L-C$ consisting of $R = R_s + R_g(t)$, $L = 2(L/2)$, and C . Applying some freshman physics, the expected current response of this basic circuit (assuming $R_g(t)$ either constant or much smaller than R_s) is a damped sinusoid with period

$$\tau_{osc} = 1/\{1/LC - R^2/4L^2\}^{1/2} \quad (1)$$

and an envelope decay time constant for the circuit of

$$\tau_{ckt} = 2L/R. \quad (2)$$

Now we note that, first, the time duration of each electrical pulse is expected to be τ_{ckt} and, second, the maximum energy available to generate sound is the electrical energy dissipated in the spark gap. The latter is approximately the integral over τ_{ckt} of the power, P_{gap} , dissipated in the gap:

$$P_{gap} = [i(t)]^2 R_g(t) \quad (3)$$

We want to maximize the time-averaged product in equation (3) in order to maximize the conversion of electrical energy into acoustic energy. Meanwhile, R_s should be minimized to both increase the pulse width (τ_{ckt}) and reduce the electrical power losses $[i(t)]^2 R_s$. When an electrical arc forms in air, the effective resistance of the arc is initially very high and the current is zero. As the ions multiply in the forming plasma channel, the arc resistance falls rapidly until it reaches a very low value (milliohms). Meanwhile, $i(t)$ rises, limited initially by $R_g(t)$ and then by the circuit inductance. As a result, P_{gap} is expected to reach a maximum very early (within a microsecond) after initiation of a discharge. A measured current waveform for the SADAG circuit during a discharge is shown in figure 4. For $C = 4\text{ }\mu\text{F}$ and lead lengths to the spark gaps of about 50 cm, τ_{osc} and τ_{ckt} were about 20 and 100 μs , respectively. By remeasuring τ_{osc} and τ_{ckt} while adding series resistance and applying equations (1) and (2), we determined that the total circuit resistance, R_s , was typically about $0.05\text{ }\Omega$ over a discharge cycle. Therefore $R_g(t)$ integrated over the discharge period must be very small, as expected. We conclude that most of the conversion of electrical energy from the discharge circuit into heated/ionized air in the spark gaps probably takes place in the early stages of the gap breakdown (in less than a microsecond) while R_g is still relatively large. As a consequence, we also conclude that a series of small discharges should be more efficient at coupling energy into the air than a single large discharge of equivalent energy. This is part of the rationale for the multiple-discharge source. In one test, the acoustic outputs from two separate spark gaps operating at 10 kV from 6- μF capacitor banks were superimposed by timing (see below); the combined peak output averaged about 16 percent (1.3 dB) greater than that of one gap operating at 10 kV from a 12- μF capacitor bank.

The use of multiple discharges also provides some flexibility for "tuning" the waveshape of the acoustic

pulse output. In normal operation of the SADAG, the rearmost spark gap is triggered first. The expanding plasma between the spark gap electrodes generates a roughly spherical expanding shock wave in the air. The position of the end plate at the rear of the arc tube can be adjusted to reflect the rearward-traveling portion of the shock wave toward the front to reinforce the trailing edge of the forward-moving portion of the pressure pulse. The firing of the second and third gaps can also be timed to either reinforce the peak of the pressure pulse from the first gap or to extend the duration of that pulse.

The version of SADAG shown in figure 5 uses a conical (linear taper) horn to more efficiently couple the pressure pulses generated in the arc tube to the air and to improve directivity.

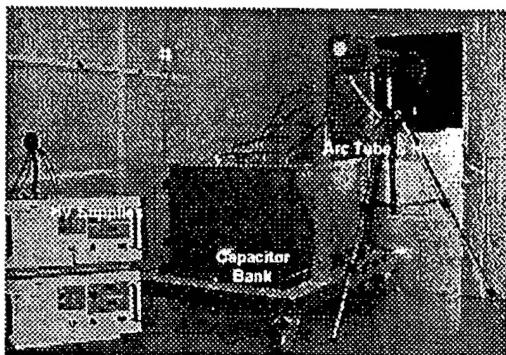


Figure 5. SADAG in position for target effects experiment.

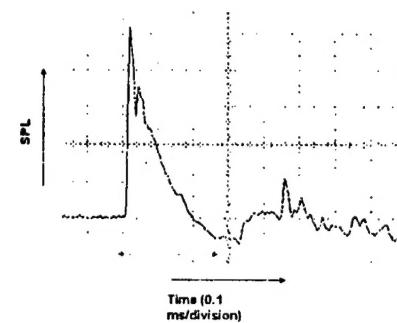


Figure 6. Waveform of a SADAG pulse (see text).

III. Performance of the Device

Figure 5 shows the SADAG configured for a laboratory effects experiment. For this experiment, two HV power supplies (shown on the left of the figure) were operated in parallel to provide rapid capacitor charging and support source operation at 12 kV or higher at pulse repetition rates to 20 Hz. The capacitors, charging resistors, and trigger circuitry were contained in the box; the arc tube and horn were mounted on the tripod. The source control circuitry (arming and firing box, trigger pulse generator) was located outside the test cell and was connected to, but electrically isolated from, the power supplies and trigger circuitry by fiber optic links. In the configuration shown, the conical horn yielded about 10 dB gain in peak SPL on-axis with respect to the arc tube alone, and the SADAG produced a reasonably uniform acoustic field (-3 dB at edges) over a 1-m diameter circle at a range of 1 m. Figure 6 shows a typical waveform of a single acoustic impulse produced by the source as measured with a precision microphone at 1 m on-axis from the mouth of the horn. The source was operated with three spark gaps and the timing of the three discharges was adjusted to maximize the recorded peak positive SPL. For this case, the capacitor charging voltage was 10 kV and the measured peak SPL was 2760 Pa, or 163 dB; the positive pulse width measured at the baseline (to first zero crossing) was 0.20 μ s. The source was operated in single pulse mode and in bursts of up to 200 pulses at rates from 5 to 20 pulses/s and (at the higher voltages, at reduced pulse repetition rates) with charging voltages from 8 to 15 kV. Over this range, the peak SPL varied from approximately 162 to 165 dB.

IV. Vortex Formation

In the course of characterizing the performance of the SADAG, we found that with the proper choice of output tube it can reliably and repeatably produce toroidal vortices along with its acoustic output. Figure 7 shows plots of SPL as a function of time (2 ms/division) for an array of four microphones spaced 0.5 in. apart along a vertical line perpendicular to the axis of the source and at a range of 0.5 m from the mouth of the bare arc tube (no horn). The short positive pulse near the start of the traces is the acoustic signal with a peak SPL of about 3000 Pa (164 dB); the ~1.5-ms negative signal with an SPL near 10 kPa (174 dB) that appears 10 ms later is the signature of a vortex. The arrival time indicates a vortex linear velocity of about 50 m/s. By "scanning" the microphone array across the source axis and repeatedly firing the source, a pressure profile of the vortex was

developed (fig. 8a). At 0.5 m, the vortex toroid has an apparent diameter of about 2 1/2 in.--just slightly larger than the diameter of the arc tube. A likely cross section for the vortex is shown in figure 8b. The ease of use and accurate output repeatability of the SADAG may make it useful as a research tool to support the development of "vortex guns" for nonlethal applications.

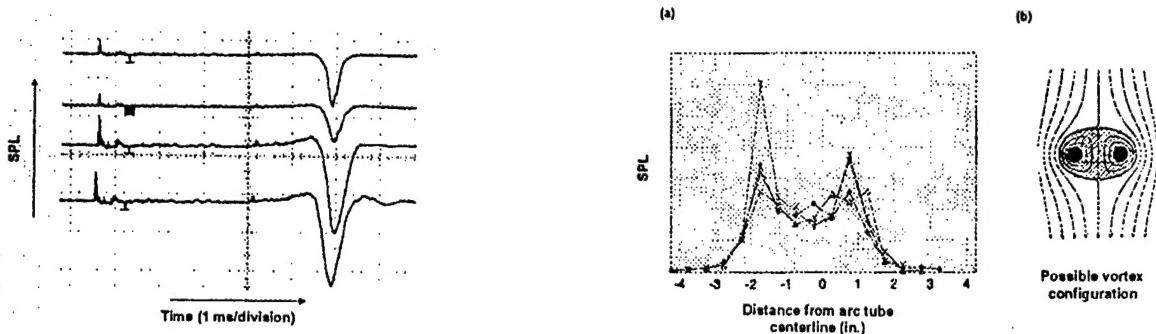


Figure 7. SPL as a function of time measured with four sensors at 0.5 m from SADAG showing vortex signature (see text).

V. Future Work

The SADAG is undergoing continuous development to upgrade its acoustic power output, waveform, and general usefulness to the nonlethal program as a repetitive ICS simulator. Currently, we are placing emphasis on increasing pulse width to better simulate the output of larger detonative sources. We are also examining the extension of this technology to fixed, indoor area-denial nonlethal weapons applications.

VI. Conclusions

In under six months, we developed an all-electrical high-power acoustic source that has found application as a laboratory simulator for potentially fieldable combustion- or detonation-driven nonlethal acoustic weapons. In laboratory environments, the device reliably produces impulsive waveforms and acoustic power levels similar to those expected from the larger developmental devices. The use of multiple electrical discharges both increases the efficiency and acoustic power output of the device and allows some flexibility for adjusting the waveshape. The capability to generate the impulses at rates to 20 Hz allows investigation of the effect of repetitive impulsive waveforms on targets.

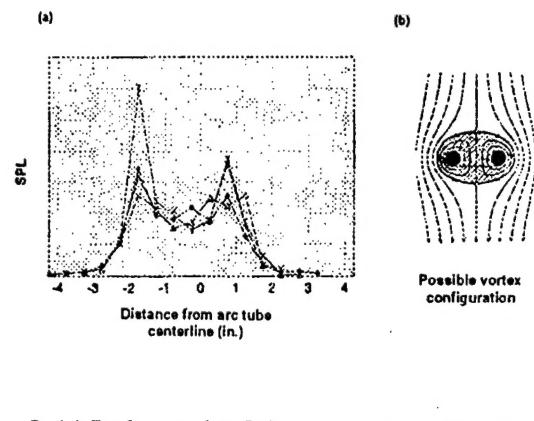


Figure 8. (a) Peak negative SPL measured as a function of sensor position in plane perpendicular to SADAG axis using repeated SADAG pulses. (b) Possible cross section of toroidal vortex that may be inferred from data in (a).